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Assessment of adsorber bed designs in waste-heat driven adsorption cooling systems for vehicle air conditioning and refrigeration

Amir Sharafian, Majid Bahrami *

Laboratory for Alternative Energy Conversion (LAEC), School of Mechatronic Systems Engineering, Simon Fraser University, BC, Canada V3T 0A3

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ABSTRACT

Adsorber bed design strongly affects the performance of waste-heat driven adsorption cooling systems (ACS) for vehicle air conditioning and refrigeration (A/C–R) applications. Adsorber beds should be specifically sized for vehicle A/C–R considering the limitations of mobile applications. However, there is no conclusive evidence on what type of adsober bed is proper for vehicle applications. To evaluate the performance of ACS, specific cooling power (SCP), adsorber bed to adsorbent mass ratio, and coefficient of performance (COP) are introduced and their order of importance are assessed. To investigate the available studies in the open literature, desired SCP of 350 W/kg dry adsorbent and adsorber bed to adsorbent mass ratio of less than one are calculated for a 1-ton-of-refrigeration, 2-adsorber bed, silica gel–water ACS. According to these criteria, previous studies are summarized into nine groups with respect to their adsober beds and consequently, finned tube adsorber bed design is selected among the existing designs. Finally, optimization of fin spacing and fin height, and enhancing thermal conductivity of adsorbent material by adding metal wool inside the finned tube adsorber bed are proposed as the practical solutions to increase heat and mass transfer rates within the adsorber bed.

Contents

1. Introduction

Refrigeration systems consume a considerable amount of energy to produce cooling power in domestic and industrial applications such as ice-making [1–3] and food industries [4–6], vaccine protection [7–9], and air conditioning applications [10–13]. Vapor compression refrigeration cycles (VCRCs) are the most popular type of refrigeration systems in which different refrigerants such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) [14] are used. Ozone depletion and global warming resulting from such refrigerants are direct environmental impacts of VCRCs. An ideal refrigeration system should use a refrigerant which has favorable thermodynamic properties and be noncorrosive, nontoxic,

* Corresponding author. Tel.: +1 778 782 8538; fax: +1 778 782 7514.
E-mail addresses: asharafi@sfu.ca (A. Sharafian), mbahrami@sfu.ca (M. Bahrami).

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Nomenclature

COP	coefficient of performance
c_p	specific heat capacity at constant pressure, (J/kg/K)
Δh_{ads}	enthalpy of adsorption, (J/kg)
HEX	heat exchanger
h	enthalpy, (J/kg)
m	mass, (kg)
Q	total heat transfer, (J)
SCP	specific cooling power, (W/kg dry adsorbent)
SS	stainless steel
T	temperature, (K)
t	time, (s)
VSCP	volumetric specific cooling power, (W/m^3 adsorber bed)

Greek symbols

τ_{cycle}	cycle time, (s)
ω	adsorbate uptake, (kg adsorbate/kg dry adsorbent)

Subscripts

bed	adsorber bed
cond	condenser
evap	evaporator
iba	isobaric adsorption
ibd	isobaric desorption
ic	isosteric cooling
ih	isosteric heating
sat	saturation
sorbent	adsorbent

non-flammable, and environmentally benign [15]. Therefore, development of green, sustainable refrigeration systems which utilize environmentally friendly refrigerants is of great importance.

The negative impacts of air conditioning and refrigeration (A/C–R) systems become more pronounce in automotive and transportation applications where a VCRC compressor is powered by mechanical energy from the internal combustion engine (ICE). Current A/C–R systems significantly increase fuel consumption and greenhouse gas production. The U.S. annually consumes about 40 billion liters of fuel for heating, ventilation, and air conditioning (HVAC) systems of light duty vehicles [16]. A VCRC compressor can add up to 5–6 kW peak power draw on a vehicle's engine, the equivalent power required for a 1200-kg sedan cruising at 56 km/h [16].

In an ICE vehicle, almost 70% of total fuel energy is dissipated through the ICE coolant and exhaust gas in the form of waste heat [16]. To retrieve the waste heat and reduce the negative impacts of VCRCs, an alternative solution is adsorption cooling systems (ACS) in which adsorber beds replace the compressor. A portion of ICE waste heat is sufficient to run an ACS to meet the A/C–R needs of a vehicle [17]. ACS, also, can be applied in natural gas vehicles (NGVs) similarly to the gasoline-powered vehicles because the exhaust gas of the engine is available. However, in hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) the exhaust gas of the engine is not available continuously. The required heat to regenerate the adsorber beds can be supplied from a heat storage tank and/or the electric motor and battery cooling systems. In the case of electric vehicles (EVs), similarly, the waste heat energy can be supplied from the electric motor and battery cooling systems. As such, proper implementation of ACS in vehicles has the potential to significantly reduce fuel consumption and minimize the carbon footprint of vehicles.

ACS work based on the sorption phenomenon in which a fluid (adsorbate) is adsorbed at the surface of a solid material (adsorbent). Most popular working pairs used in ACS include zeolite–water, silica gel–water and activated carbon–methanol. These materials are environmentally friendly, non-toxic, non-corrosive, and inexpensive [18]. Moreover, ACS are quiet and easy to maintain [19] as there is no moving part, except valves, in these systems. Thus, ACS are ideal candidates for a variety of applications especially where waste-heat or low-grade thermal energy is available. However, commercialization of ACS faces major challenges; namely: (i) low specific cooling power (SCP) and (ii) low coefficient of performance (COP) that result in heavy and bulky A/C–R systems which make them impractical for vehicle A/C–R applications [20]. The origin of the ACS low performance is low thermal conductivity of adsorbent materials due to high porosity and thermal contact resistance between the adsorbent particles, for example, thermal conductivity of zeolite 13X, silica gel–$CaCl_2$ and activated carbon are 0.1, 0.12 and 0.3 W/m/K, respectively [21–23]. As a result, heating and cooling of ACS adsorber beds are time consuming processes. As such, design and optimization of an adsorber bed with improved heat and mass transfer characteristics, and low adsorber bed to adsorbent mass ratio can effectively increase the SCP and COP of ACS [24–26].

In this paper, an in-depth assessment of available adsorber bed design of waste-heat driven ACS is presented with a focus on vehicle A/C–R applications. The previous studies are classified based on the ACS working pairs, cooling capacity, cycle time, COP, SCP, and adsorber bed to adsorbent mass ratio. Based on these data, the effects of different adsorber bed designs are investigated on the SCP, adsorber bed to adsorbent mass ratio and COP to identify the best adsorber bed designs suitable for vehicle A/C–R applications. Finally, several practical solutions and remedies are proposed to improve the performance of ACS.

2. Adsorption versus absorption

Adsorption is, in general, the adhesion of ions or molecules of gases, liquids or dissolved solids to a solid surface [27]. Adsorption phenomenon is an exothermic process in which molecules of a liquid or gas, called adsorbate, accumulate on a solid surface, called adsorbent [28,29]. Adsorbents are porous materials with ability to take up several times of their volume of gases or liquids. The terms “adsorption” and “absorption” are usually assumed to be the same, but they are, in essence, completely different physical phenomena. In the adsorption process, molecules of gas or liquid adhere on the surface of the solid, whereas in the absorption process, molecules of gas or liquid penetrate into the solid or liquid phase.

3. Thermodynamic cycle of ACS

ACS work based on two main steps: heating–desorption–condensation and cooling–adsorption–evaporation. Using these steps, the ACS produces evaporative cooling power intermittently. To produce continuous cooling power, the solution is to use more than one adsober bed. Fig. 1a depicts the schematic of a 2-adsorber bed ACS. The main components of an ACS consist of adsorber beds, condenser, expansion valve, and evaporator. Therefore, the ACS is similar to the VCRC, except that the adsorber beds replace the compressor.

Thermodynamic cycle of an ACS, Fig. 1b, includes four processes: (1) Isosteric heating (ih), process 1–2; (2) Isobaric desorption (ibd), process 2–3′; (3) Isosteric cooling (ic), process 3′–4′; and (4) Isobaric adsorption (iba), process 4′-1. During step 1–2, adsorbent-adsorbate pair through an isosteric process, absorbs heat in amount of Q_{ih} from an external heat source. In this step, temperature and pressure of the adsorber bed increase due to the adsorbate desorption from the adsorbent particles. This process is continued until the pressure of adsorber bed reaches the pressure of condenser. At this time, the entrance valve to the condenser is opened [19].

In step 2–3′, the external heat source continuously heats the adsorber bed (Q_{ibd}) during an isobaric desorption process and the adsorbate leaves the adsorber bed and is condensed inside the condenser during an isobaric cooling process (step 2–3) [19]. After heating the adsorber bed up to the point 3′ which is the maximum temperature of the cycle, the valve between the adsorber bed and the condenser is closed and during an isosteric cooling process (step 3′–4′), the adsorbent loses its heat (Q_{ic}) in contact with a heat sink [19]. In step 3–4, the adsorbate inside the condenser passes through the expansion valve and enters to the evaporator. During step 4–1, the adsorbate absorbs heat in amount of Q_{evap} from the environment of interest and converts to the vapor. At the same time, the entrance valve to the adsorber bed is opened and the adsorbent adsorbs the vapor adsorbate during an isobaric adsorption process (step 4′–1) and releases its heat (Q_{ibd}) [19].

Waste-heat of engine and solar energy can be utilized to desorb adsorbate from adsorbent during the desorption process. Waste-heat and solar driven ACS for ice making and building A/C applications have been discussed at length in literature [25,31–34]. Although many attempts carried out to improve the performance of ACS, the available systems are still bulky thus not suitable for vehicle A/C–R applications. Adsorbent–adsorbate pair, thermodynamic cycle, and adsorber bed are effective factors on the performance of ACS.

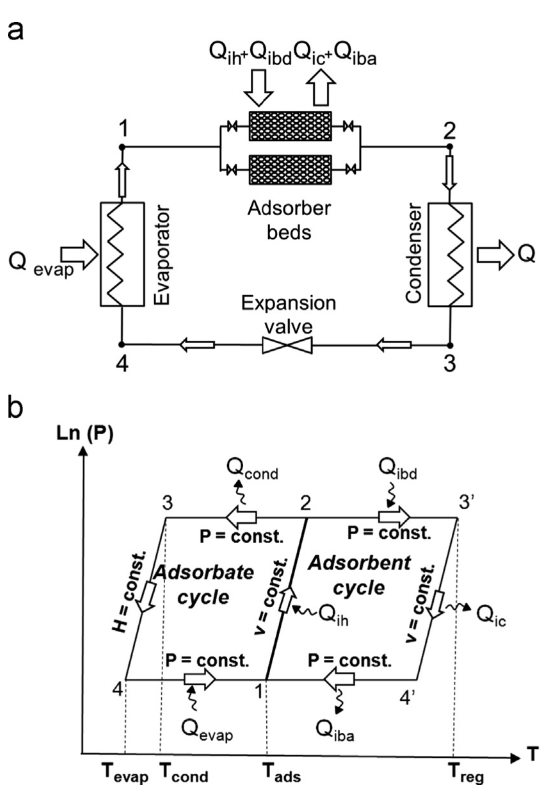


Fig. 1. (a) Schematic, and (b) Thermodynamic cycle of a 2-adsorber bed ACS [30].

3.1. Adsorbent materials

Zeolite, silica gel and activated carbon are common materials applied in ACS. Recently, new composite adsorbent materials have been designed with higher sorption rate such as zeolite–$CaCl_2$ and silica gel–$CaCl_2$. More information about adsorption working pairs was reported by Wang et al. [35]. Adsorbent materials are porous particles with low thermal conductivity. Also, thermal contact resistance between the adsorbent particles reduces the overall thermal conductivity of the adsorber beds [10,36–38]. Beside, adsorbate diffusion coefficient through the solid adsorbent particles is small. For instance, water vapor diffusion coefficient in a 2-mm silica gel bead is in the order of 10^{-10}–10^{-12} m^2/s [39].

3.2. Different ACS thermodynamic cycles

Different adsorption cycles were designed for proof-of-concept demonstrations. The simplest cycle is single-bed ACS which work intermittently such as solar driven ACS. To produce continuous cooling power, two- to six-bed ACS have been designed [40–45]. Although multi-bed ACS provide continuous cooling, they are more complex, heavier and bulkier than the single-bed ACS. Fig. 2 shows a six-bed, silica gel–water ACS which works with 40–90 °C heat sources to produce evaporative cooling power of 1.14–4.0 kW [43]. Unfortunately, the cost of these systems has not been reported in the literature; however, according to the

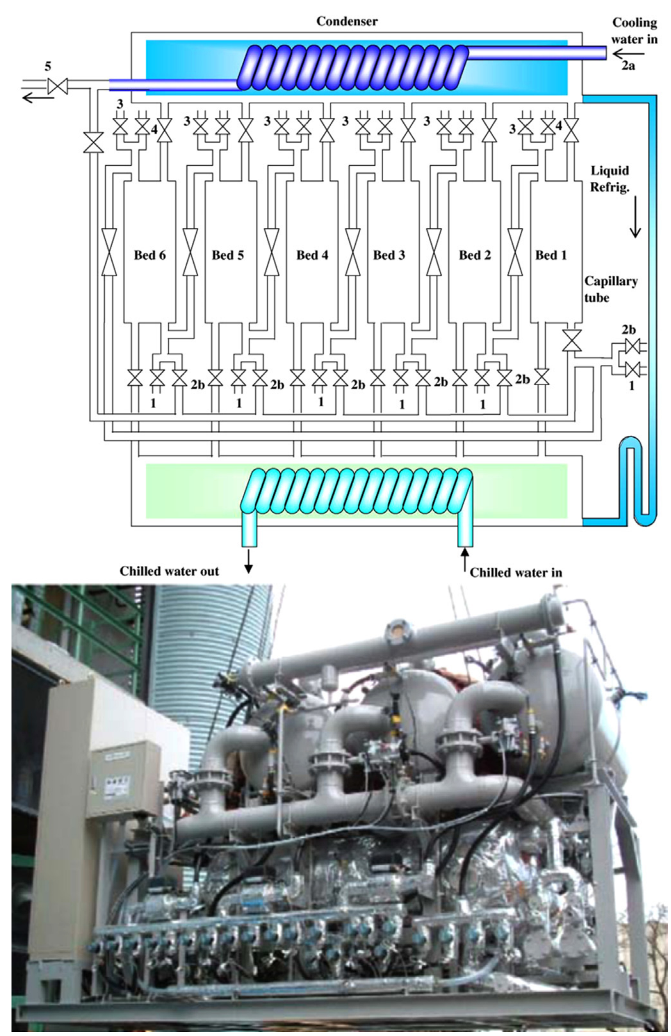


Fig. 2. A six-bed, silica gel–water, waste-heat driven ACS for building A/C applications designed by Saha et al. [43].

information prepared by SorTech AG Company who builds 8-kW adsorption cooling systems for building air conditioning applications, the cost of this system is about $27,000.

To improve the performance of ACS, some modifications are proposed such as adding heat recovery cycle [46], heat and mass recovery cycles [47], thermal wave cycle [48], forced convective thermal wave cycle [49], and cascade cycle [50,51]. In an ACS with heat recovery cycle, heat is transferred to the heat transfer fluid from a hot bed at the end of the desorption process to a cold bed at the start of the desorption process to recover heat between two or more adsober beds. In heat and mass recovery cycles, which borrow the same concept as the heat recovery cycle, heat is transferred to the heat transfer fluid from the hot bed to the cold bed, and adsorber beds are, also, directly connected to each other. In the mass recovery cycle, a hot bed with high pressure at the end of desorption process is connected to a cold bed with low pressure at the start of desorption process. Due to the pressure gradient between the beds, the remainder of the adsorbate inside the hot bed with high pressure is transferred to the cold bed which is at low pressure. The advantage of heat and mass recovery cycles is that they do not add more complexity to the system while significantly increase the performance of ACS. Adding heat and mass recovery cycles to a 2-adsorber bed ACS can increase the COP up to 30% [52,53]. Also, Qu et al. experimentally showed that adding only mass recovery cycle to the ACS can increase the cooling capacity by 20% [52]. The other modifications have some limitations and complexities; more detailed information is available elsewhere, e.g. [54]. Heat and mass recovery cycles are mainly of interest for building A/C applications where the amount of waste heat is limited and the COP is a major concern. In vehicles, however, waste-heat is abundant and added weight, cost and complexity due to the heat recovery cycle are problematic. As such, ACS with only mass recovery cycle suffices for vehicle A/C–R applications.

4. Important parameters to evaluate the performance of ACS

The SCP, adsorber bed to adsorbent mass ratio, and COP are the three main parameters used to evaluate the overall performance of ACS in this study.

4.1. Specific cooling power (SCP)

It is defined as the ratio of evaporative cooling energy to the mass of dry adsorbent multiplied by the cycle time, Eq. (1). The SCP represents the amount of cooling power produced per unit mass of dry adsorbent.

$$\mathrm{SCP} = \frac{Q_{evap}}{m_{sorbent}\tau_{cycle}} \; (W/\text{kg dry adsorbent}) \tag{1}$$

where Q_{evap} is the evaporative cooling energy (J), $m_{sorbent}$ is the mass of dry adsorbent (kg) and τ_{cycle} is the cycle time (s), respectively. Eq. (2) defines Q_{evap}:

$$Q_{evap} = m_{sorbent} \int_{\substack{adsorption\\ time}} (h_{sat,\ vapor@T_{evap}} - h_{sat,\ liquid@T_{cond}}) \frac{d\omega}{dt} dt \; (J) \tag{2}$$

where ω is the adsorbate to dry adsorbent mass ratio (kg/kg dry adsorbent), $d\omega/dt$ is the adsorbate sorption rate by adsorbent particles, and h_{sat} is the adsorbate saturation enthalpy (J/kg), respectively. Adsorbate sorption rate represents the amount of adsorbate uptake by the adsorbent particles as a function of time. By substituting Eq. (2) in Eq. (1), the SCP is expressed as follows:

$$SCP = \frac{1}{\tau_{cycle}} \int_{\substack{adsorption\\ time}} (h_{sat,\ vapor@T_{evap}} - h_{sat,\ liquid@T_{cond}}) \frac{d\omega}{dt} dt \; (W/\text{kg dry adsorbent}) \tag{3}$$

Eq. (3) shows that the SCP increases by increasing adsorbate sorption rate and enthalpy difference, and decreasing the cycle time. Adsorbate sorption rate increases by decreasing heat and mass transfer resistances within the adsober bed as well as designing new adsorbents with higher sorption rate. To increase the enthalpy difference inside the evaporator, a practical solution is to install a receiver tank between the condenser and the expansion valve. The receiver tank helps to accumulate sub-cooled liquid adsorbate at the outlet of condenser. Sub-cooling is a process by which a saturated liquid adsorbate is cooled below the saturation temperature of condenser.

The SCP of ACS for vehicle A/C–R applications should be maximized since the foot-print and weight of A/C–R system are of great importance. A typical value for the SCP of waste-heat driven ACS reported in open literature is 80–150 W/kg dry adsorbent. However, the current SCP definition, Eq. (3), does not show all aspects of ACS performance. The deadweight and volume of the adsorber beds are not included in the above SCP definition. For example, consider a thin layer of adsorbent that is coated on the surface of an adsorber bed; The resulting SCP value becomes large due to small heat and mass transfer resistances inside the bed which result in high adsorbate sorption rate and, consequently, short cycle time. However, the weight and volume of the adsorber bed create an excessively large and bulky system. Such very high SCP values were reported by Critoph et al. [23,55–58]. Besides, the adsorbent mass does not directly affect the SCP value, as shown in Eq. (3); this can be misinterpreted by the unit of SCP (W/kg dry adsorbent). The term that affects the SCP value is the adsorbate sorption rate, $d\omega/dt$. To overcome this issue and describe accurately the compactness of ACS, the following parameters are recommended for the evaluation of ACS performance:

- Volumetric specific cooling power (VSCP) which shows the effects of adsorber beds volume:

$$\mathrm{VSCP} = \frac{Q_{evap}}{V_{bed}\tau_{cycle}} \; (W/m^3 \text{ adsorber bed}) \tag{4}$$

  where V_{bed} is the adsorber beds total volume (m^3).
- Adsorber bed to adsorbent mass ratio which represents the ratio of dead to live masses. When heating or cooling the adsorbent particles, the adsorber bed metal is, also, heated up or cooled down. Therefore, lower metal mass results in faster heating and cooling of adsorbent particles in a shorter cycle time, and consequently, higher SCP.

4.2. Coefficient of performance (COP)

To evaluate the efficiency of refrigeration cycles, a dimensionless parameter called COP is used. In ACS, the COP is defined as the ratio of evaporative cooling energy to the amount of supplied heat, Eq. (5).

$$\mathrm{COP} = \frac{Q_{evap}}{Q_{waste\ heat}} \tag{5}$$

where Q_{evap} and $Q_{waste\ heat}$ are the evaporative cooling energy (J) and the amount of waste heat energy supplied during the

desorption process (J), respectively. Eq. (6) defines $Q_{waste\ heat}$:

$$Q_{waste\ heat} = m_{sorbent} \int_{desorption\ time} \left[\left(c_{sorbent} + c_{p,\ liquid\ adsorbate}\, \omega + \frac{m_{bed}}{m_{sorbent}} c_{bed} \right) \frac{dT}{dt} - \Delta h_{ads} \frac{d\omega}{dt} \right] dt\ (J) \quad (6)$$

where $m_{bed}/m_{sorbent}$ is the adsober bed to adsorbent mass ratio, c_p is the specific heat capacity at constant pressure (J/kg/K) and Δh_{ads} is the enthalpy of adsorption (J/kg), respectively. As shown in Eqs. (2) and (6), to increase the COP under constant evaporation and condensation temperatures, the adsorbate sorption rate, $d\omega/dt$, should be increased and the adsorber bed to adsorbent mass ratio, $m_{bed}/m_{sorbent}$, should be decreased. The COP is important where the supplied energy is costly and limited, such as hot water in buildings.

4.3. Desired range for the performance of ACS

The cooling power required for A/C of a subcompact vehicle is approximately 1 t of refrigeration (TR) [17,42], which is equal to 3.517 kW. Lambert and Jones [41] showed that the total daily commute time in the U.S. is about 40 min, ≈20 min to work and ≈20 min returning home. A properly sized A/C of a light-duty vehicle should be able to cool down the cabin temperature within 10 min after start-up [59,60]. As a result, adsorption and desorption times in a 2-adsorber bed ACS with 10 min cycle time is 5 min (300 s). For example, the amount of water, which should be circulated through a 2-adsorber bed, silica gel–water ACS, to supply 1-TR cooling power is equal to:

$$m_{adsorbate} = \frac{\dot{Q}_{evap}(\mathrm{kW}) \times \Delta t_{adsorption}(\mathrm{s})}{h_{sat,\ water\ vapor@T_{evap}=10\ ^\circ C} - h_{sat,\ liquid\ water@T_{cond}=45\ ^\circ C}(\mathrm{kJ/kg})} = \frac{3.517 \times 300}{2519.2 - 188.44} = 0.453\ \mathrm{kg} \quad (7)$$

It should be noted that the amount of discharged adsorbate depends on the adsorbent particles filled inside the adsorber bed; here, silica gel is used for the calculation as it can work with low temperature heat sources (<90 °C) such as engine coolant. The amount of equilibrium water uptake of silica gel particles is about $\omega = 0.185$ kg/kg dry silica gel at 35 °C and 1.2 kPa, which is equal to the evaporator saturation pressure at 10 °C, and $\omega = 0.05$ kg/kg dry silica gel at 90 °C and 9.6 kPa, which is equal to the condenser saturation pressure at 45 °C [61,62]. However, in a real adsorption cycle, adsorbent does not fully saturated with adsorbate during the adsorption process and it does not completely dry out during the desorption process. It has been shown that a typical water uptake and discharge difference for silica gel particles, $\Delta\omega$, is approximately 0.09–0.1 kg/kg dry silica gel [62]. Therefore, the amount of silica gel per adsorber bed is calculated as follows:

$$m_{sorbent} = \frac{m_{adsorbate}}{\Delta\omega} = \frac{0.453}{0.09} = 5\ \mathrm{kg\ dry\ silica\ gel/bed} \quad (8)$$

By substituting the calculated parameters in Eq. (1), the maximum SCP of a 2-adsorber bed, silica gel–water ACS can be estimated as follows:

$$SCP_{max} = \frac{\dot{Q}_{evap} \times \Delta t_{adsorption}}{m_{sorbent} \tau_{cycle}} = \frac{3.517 \times 10^3 \times 300}{5 \times 600} \approx 350\ W/\mathrm{kg\ dry\ adsorbent} \quad (9)$$

To reach the maximum SCP, an adsorber bed with the following characteristics is required: (i) high heat transfer surface area to increase heat transfer rate, and (ii) low adsorbent thickness to increase mass transfer rate. To design an adsorber bed with such characteristics, the amount of utilized metal (dead mass) increases significantly. A critical factor for auxiliary systems designed for vehicle applications is dead mass which should be minimized. Therefore, the adsorber bed to adsorbent mass ratio in an ACS should be reduced. Here, the goal is to reach the ideal adsorber bed to adsorbent mass ratio of less than one.

The COP of waste-heat driven ACS is less than that of VCRCs. Meunier [63] theoretically showed that the COP of an ACS with an infinite number of cascades reaches 1.8; however, the practical COP of ACS is about 0.3–0.4. In vehicle A/C–R applications, the COP of ACS is not as important as the SCP and adsorber bed to adsorbent mass ratio because the supplied heat comes from the ICE coolant and/or the exhaust gas. However, ACS with higher COP are preferred. In brief, the order of importance to evaluate suitability of a waste-heat driven ACS for vehicle A/C–R applications are: (i) high SCP; (ii) low adsorber bed to adsorbent mass ratio; and (iii) high COP.

5. Comparison of existing ACS adsorber bed designs

A number of literature reviews have been published on waste-heat driven ACS with a focus on challenges and opportunities facing ACS development; however, they lack practical solutions toward design of efficient adsorber beds for waste-heat driven ACS; for more information refer to Ref. [19,34,35,54,64–78].

To increase heat and mass transfer within an adsorber bed, different heat exchangers are used in previous studies. Fig. 3 shows nine different types of adsorber beds used in different experiments/studies of waste-heat driven ACS.

The main goals of using heat exchangers in adsorber beds are to increase heat transfer surface area between the heat transfer fluids and adsorbent particles during adsorption and desorption processes, and to decrease mass transfer resistance between adsorbate and adsorbent particles. However, there is no conclusive evidence on which types of adsorber bed are suitable for vehicle A/C–R applications. To find proper adsorber bed types, the data reported in the literature is summarized in Table 1 based on working pairs, cooling capacity, COP, SCP, cycle time, and adsorber bed to adsorbent mass ratio. To compare the data tabulated in Table 1, we tried to extract the reported cooling capacity, SCP and COP of ACS at evaporation and condensation temperatures of 10 and 45 °C, respectively; these temperatures are in agreement with those of required for vehicle A/C purposes. Also, minimum and maximum temperatures of the adsorber beds are set at an adsorption temperature of 45 °C, and a regeneration temperature of 90 °C for silica gel and activated carbon, and 180 °C for zeolite; however, in some studies, the performance of ACS was not available in the operating temperatures mentioned above.

As shown in Table 1, different working pairs are utilized in waste-heat driven ACS. Silica gel desorbs water using low temperature heat sources (<90 °C) which is appropriate for A/C applications. Activated carbon is another adsorbent material which works with higher temperature heat sources (<130 °C) and adsorbs different adsorbates such as ethanol, methanol and ammonia. Beyond 140 °C, methanol is dissociated at the presence of activated carbon as it acts as a catalyst for methanol [46]. The condenser and evaporator pressures in the ACS are fixed by the adsorbate saturation pressures at condensation and evaporation temperatures, respectively. As a result, ACS, which work using water, methanol, or ethanol as an adsorbate, operate under vacuum pressures, while activated carbon–ammonia ACS work above atmospheric pressures. Lambert and Jones [41,42], and Critoph et al. [12,70,93,94] designed activated carbon–ammonia ACS for vehicle A/C–R applications; however, we do not

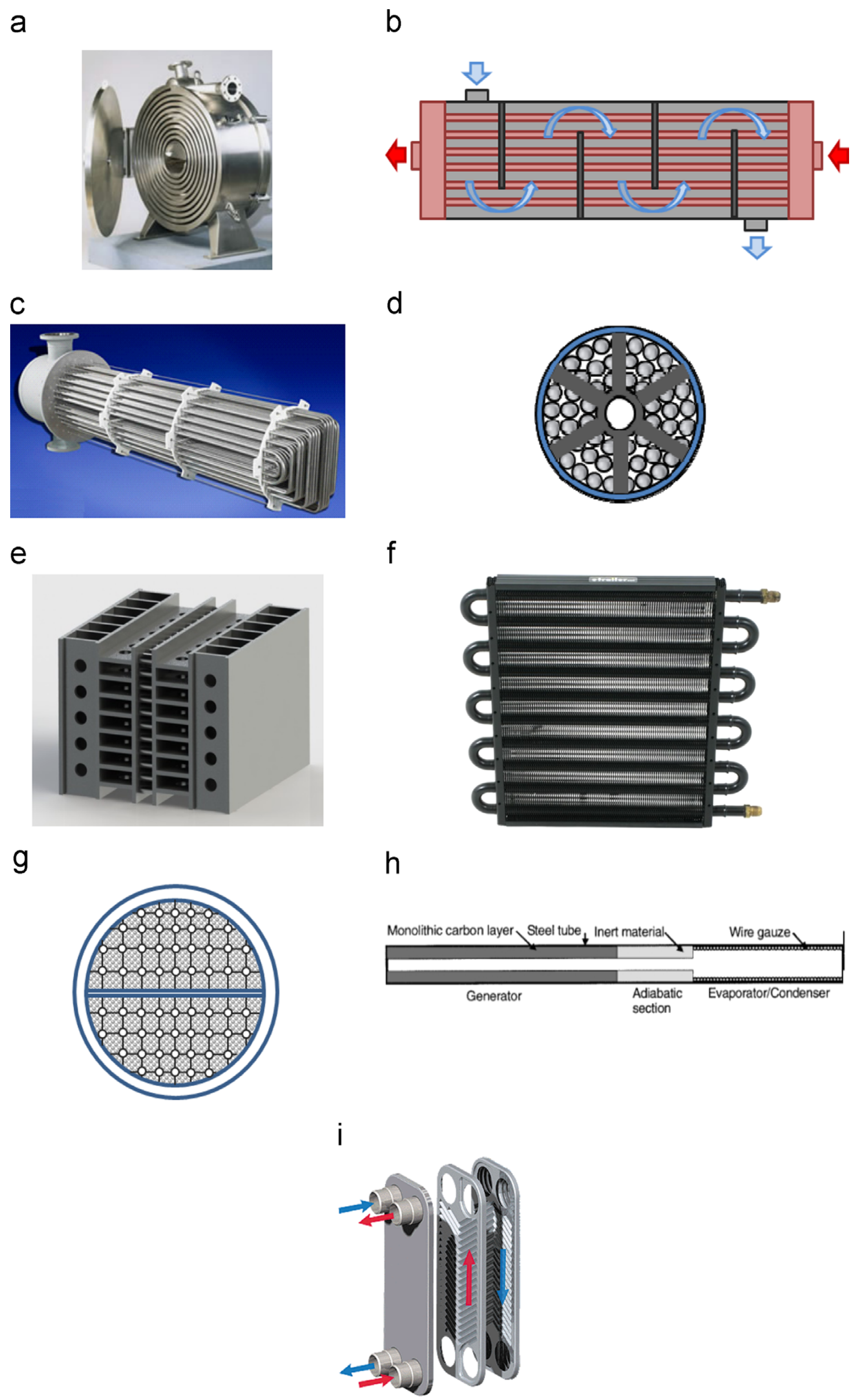


Fig. 3. Various heat exchanger types used as adsorber bed of waste-heat driven ACS. (a) Spiral plate [20,79], (b) Shell and tube [80,81], (c) Hairpin [51], (d) Annulus tube [82], (e) Plate fin [83–85], (f) Finned tube [86–88], (g) Plate-tube [52,53,67,89–91], (h) Simple tube [23,55–58], (i) Plate [92].

recommend them for vehicle A/C–R applications because of the poisonous nature of ammonia.

Zeolite can work with high temperature heat sources (> 180 °C) such as exhaust gas of engine which is at least 400 °C at the idle condition [120,121]. Zeolite is more durable than silica gel and activated carbon [122]. For instance, water uptake capacity of zeolite Na-13X reduces by 20% after 3500 cycles of adsorption and desorption, whereas adsorbate uptake capacity of silica gel and activated carbon reduces by 35% after 1600 cycles [122]. Moreover, adsorbate uptake capacity of zeolite is more than that of activated carbon and silica gel. In other words, to uptake a specific amount of adsorbate, less amount of zeolite is required compared with activated carbon and silica gel. The other important factor for vehicle A/C–R systems is adsorbent density which affects the bulkiness of adsorber bed. Density of zeolite and silica gel beads are about 800 [10] and 700–750 kg/m^3 [123], respectively, whereas density of activated carbon pellets is between 400–500 kg/m^3 [23]. Therefore, volume of adsorber beds filled

Table 1
Summary of existing studies on waste-heat driven ACS for A/C–R application. Summary of existing studies on waste-heat driven ACS for A/C–R application.

Reference no.	Working pairs	Cooling capacity	Cycle time (min)	COP	SCP (W/kg)	Adsorber bed info.	Adsorbent mass	Adsorber bed to adsorbent mass ratio
[51]	Zeolite/water, Act. carbon/ methanol	1.44 kW[a], (14351 kJ)	164	0.65[a]	23[a]	3 Copper hairpin HEX, 3 × 118 kg	12.5+23.5+27.5=63.5 kg, 1.5 mm in dia.	9.4, 5, 4.3, Average: 6.3
[86–88]	Consolidated act. carbon/ ammonia	52.8 W[a]	20	0.061[a]	33[a]	Aluminum finned tube HEX, 4.6 kg[a]	0.8 kg	5.75[a]
[95]	Silica gel/methanol	23 W[a] (70 kJ)[a]	65	–	30[a]	SS[b] Finned tube HEX[c]	0.6 kg	–
[96–98]	Zeolite 13X/water	242.6 W (1114 kJ)	131.5	0.38	22.8[a]	SS cylindrical finned tube HEX, 31 kg	6.2 kg, 2–3 mm in dia.	5
[11,99]	Zeolite 13X/water	6 kW[a]	180, Ads./ Des.: 2/1	0.25	28.5	Finned tube HEX, 260 kg	140 kg, 3 mm in dia.	1.86
[100]	Silica gel+$CaCl_2$(SWS-1L)/ water	60 W[a]	167, Ads./ Des.: 3/4	0.43[a]	23.5[a]	SS finned tube HEX, 3.3 kg[a]	1.1 kg, 0.8–1.6 mm in dia.	3
[101]	AQSOA-FAM-Z02/water	1 kW[a]	8.6[a]	0.27[a]	131.5[a]	2 Aluminum finned tube HEX, 15 kg/bed	1.9 kg/bed	7.9
[102–104]	Silica gel/water	9.6 kW	34	0.43	48[a]	2 Finned tube HEX, 32.7 kg/bed	50 kg/bed, 0.5–1 mm in dia.	0.654
[105]	Coated hydrophobic Y zeolite (CBV-901)/ methanol	–	18[a]	0.11[a]	25[a]	SS Finned tube HEX	Coated zeolite thickness: 10 mm	3
[106]	Silica gel/water	700 W[a]	37	0.29[a]	35[a]	2 Finned tube HEX	5 kg/bed	–
[31,107–109]	Act. carbon+$CaCl_2$ (1:4)/ ammonia	680 W[a]	40[a]	0.19[a]	70.8[a]	2 Finned tube HEX	2.4 kg/bed	–
[110]	Silica gel+$CaCl_2$(SWS-1L)/ water	480 W[a]	10	0.15	137[a]	Aluminum finned tube HEX, 6.08 kg	1.75 kg	3.47
[111]	Silica gel+$CaCl_2$/water	103 W[a]	100	0.23	43	Finned tube HEX	1.2 kg	–
[112]	Silica gel/water	1.9 kW	6	0.29	158[a]	2 Aluminum finned tube HEX, 13.6 kg/bed[a]	3 kg/bed	4.53
[113,114]	$LiNO_3$–Silica KSK/water	155 W[a] (42.9 kJ)[a]	6.4 Ads./ Des.: 5/2	0.176[a]	318[a]	Aluminum finned tube HEX, 0.636 kg	0.350 kg, 0.25–0.5 mm in dia.	1.82
[82]	Consolidated graphite+zeolite 13X/ water	213 W[a]	72[a]	0.28[a]	38[a]	SS 304 annulus tube HEX, 5.18 kg[a]	2.8 kg	1.85[a]
[21]	Consolidated zeolite/water	3.14 kW[a], (5657 kJ)	60	0.41	97	2 Annulus tube HEX	8.1 kg/bed	–
[20,79]	Act. carbon/methanol	31.5 kg ice/day	100	0.2	2.63 kg ice/kg adsorbent per day	2 SS spiral plate HEX, 80 kg/bed	6 kg/bed	13.3
[52,53,67,89–91]	Act. carbon/ammonia	15.8 kW[a] (19 MJ)[a]	40[a]	0.37[a]	152[a]	2 Plate-tube HEX, 90 kg[a]/bed	26 kg/bed	3.46[a]
[80,81]	Act. carbon/methanol	1.7 kW	50[a]	0.08[a]	7.6[a]	2 Shell and tube HEX, 184.8 kg/bed	56 kg/bed	3.3
[1]	Act. carbon/ammonia	500 kJ[a]	–	0.06[a]	–	4 Shell and tube HEX, 73 kg/bed[a]	8 kg/bed	9.1[a]
[23,55–58]	Consolidated act. carbon/ ammonia	16 W	10	0.22	200	78.11 g/tube	38.78 g/tube	2.0
		42 W	3.3	0.19	550	609.97 g/tube	77.19 g	7.9
		27 W	5	0.18	350	770.66 g/tube	77.91 g	9.89
[12,70,93,94]	Consolidated act. carbon/ ammonia	1.6 kW	1	0.22	800[a]	Plate HEX, 9 kg	1 kg	9
[92]	Silica gel/water	2336 kJ[a]	4.6	0.33[a]	118[a]	2 Plate HEX	36 kg/bed	–
[115,116]	Silica gel/water	21.4 kW[a]	20	0.51[a]	57[a]	4 Plate fin HEX, 115 kg/bed	47 kg/bed	2.45
[83–85]	Silica gel/water	2.8 kW[a]	17.66	0.21[a]	26.5[a]	2 Plate fin HEX, 180 kg/bed	26.4 kg/bed, 0.5–1 mm in dia.	6.8
[117]	Silica gel/water	8.5 kW[a]	17	0.36[a]	132[a]	2 Plate fin HEX, 115 kg/bed	16 kg/bed, 0.6 mm in dia.	7.2
[118]	Silica gel/water	4.3 kW	12	0.45	87.8[a]	Flat tube HEX with corrugated fins,	24.5 kg, 0.5–1.5 mm in dia.	–
[119]	Silica gel/water	3.7 kW	45	0.5	26[a]	2 HEX, 129 kg/bed	35 kg/bed	3.7

[a] We extracted these parameters based on the reported experimental data at $T_{evap}=10$ °C, $T_{cond}=45$ °C, $T_{ads}=45$ °C, and $T_{reg}=90$ °C (for silica gel and activated carbon) and $T_{reg}=180$ °C (for zeolite).
[b] SS: Stainless steel.
[c] HEX: Heat exchanger.

with the same amount of zeolite and silica gel are 1.4–2 times smaller than those of filled with activated carbon.

Although zeolite has shown better performance than activated carbon and silica gel, it starts to desorb adsorbate at temperatures higher than 110 °C [46]. As a result, zeolite–water ACS are costly because their valves, fittings, sensors, etc. should be rated for high temperatures. To reduce the maximum temperature of ACS and increase the adsorbate uptake capacity of adsorbents, new composite adsorbent materials have been introduced, see Table 1. The composite adsorbents are usually a mixture of an inorganic salt,

such as $CaCl_2$, LiBr and $MgCl_2$, which is impregnated in an adsorbent, such as silica gel, zeolite and activated carbon. Water uptake capacity of silica gel–$CaCl_2$,called selective water sorbent (SWS), is about 0.8 kg/kg dry adsorbent [62]. More detailed information on composite adsorbents is available elsewhere, see e.g. [35,62].

6. Results and discussions

The main functions of ACS adsorber beds are to provide proper heat and mass distribution within the adsorbent particles. The proposed method to select a proper adsorber bed designs for vehicle A/C–R applications is to compare the effects of various adsorber bed types on the SCP, adsorber bed to adsorbent mass ratio, and the COP. Fig. 4 shows the effects of different adsober beds on the performance of waste-heat driven ACS according to the tabulated data in Table 1. These adsorber beds are classified into nine groups: (1) Spiral plate (2 experiments), (2) Shell and tube (3 experiments), (3) Hairpin (1 experiments), (4) Annulus tube (2 experiments), (5) Plate fin (6 experiments), (6) Finned tube (25 experiments), (7) Plate-tube (7 experiments), (8) Simple tube (5 experiments), and (9) Plate (5 experiments). In Fig. 4, to compare the performance of different ACS, averaged values of SCPs, adsorber bed to adsorbent mass ratios and COPs are calculated due to a large number of experimental data for each adsorber bed type. For convenience, the data shown in Fig. 4 are sorted according to the ascending SCP.

As mentioned in Section 4.3, the maximum SCP of 350 W/kg dry adsorbent, adsorber bed to adsorbent mass ratio of less than one and high COP are the desired values for 1-TR ACS. To this end, adsorber bed types with higher SCPs located at the right-hand side of Fig. 4 is preferred. The second criterion is the adsorber bed to adsorbent mass ratio which is equal to 6.6 and 9 for simple tube and plate adsorber beds (adsorber bed No. 8 and 9 in Fig. 4a), respectively. Therefore, these adsorber beds are not recommended for vehicle applications as the dead mass is considerable. Our analyses based on the aforementioned criteria show that annulus tube, plate fin, finned tube, and plate-tube adsorber beds result in better performance than the other adsorber beds, demarcated gray region in Fig. 4.

Among the considered bed designs, annulus tube is suitable for small cooling capacity ACS as the amount of adsorbent filled inside the bed is limited to the volume between the two tubes, see Fig. 3d. As a result, the number of adsorber beds increases significantly to supply 1TR. In addition, by increasing the space between the two tubes, the adsorbent thickness increases which results in higher heat and mass transfer resistances inside the bed, and consequently, lower SCP and COP. Plate fin adsorber bed, shown in Fig. 3e, is a compact heat exchanger which results in an average SCP of 72 W/kg dry adsorbent, average adsorber bed to adsorbent mass ratio of 5.5, and average COP of 0.36, respectively; however, vacuum sealing of this type of adsober beds may be difficult due to its geometry, a large number of units stack over each other and vehicle's vibration.

Fig. 4 also shows that finned tube and plate-tube adsorber beds can supply an average SCP of 80–150 W/kg, average adsorber bed to adsorbent mass ratio of 3.45–3.6, and average COP of 0.25–0.37, respectively. The plate-tube adsorber beds are more compact than the finned tube adsorber beds; however, adsorbate should be able to penetrate into the center of plate-tube adsorber bed, see Fig. 3g. As such, mass transfer resistance within the adsorber bed increases. To this end, these adsober beds are mainly applicable for activated carbon–ammonia ACS in which typical operating pressures of evaporator and condenser are 3 and 30 bars, respectively, and adsorbate can easily penetrate into the center of adsorber bed; whereas the operating pressure of ACS, which work with water, ethanol and methanol as an adsorbent, is

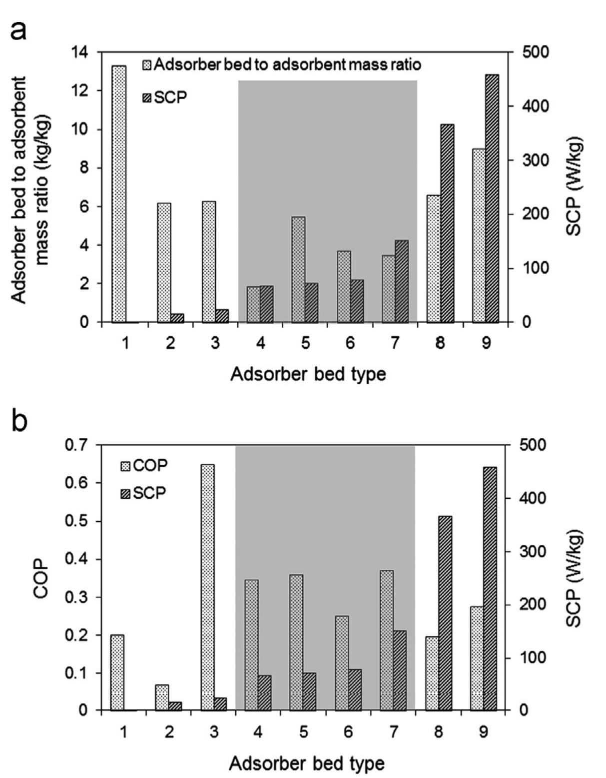


Fig. 4. Effects of different adsorber bed designs on: (a) adsorber bed to adsorbent mass ratio and SCP, and (b) COP and SCP. Adsorber bed type: (1) Spiral plate, (2) Shell and tube, (3) Hairpin, (4) Annulus tube, (5) Plate fin, (6) Finned tube, (7) Plate-tube, (8) Simple tube, and (9) Plate.

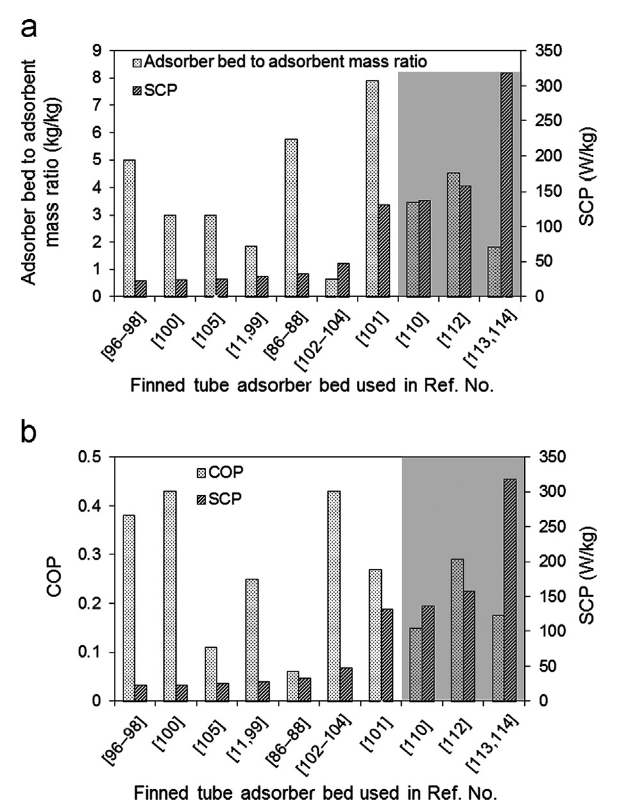


Fig. 5. Effects of different finned tube adsorber bed designs on: (a) adsorber bed to adsorbent mass ratio and SCP, and (b) COP and SCP.

below atmospheric pressure. For instance, the operating pressure of evaporator and condenser in an activated carbon–methanol ACS are 5 and 30 kPa (absolute pressure), respectively [20,79]. As a result, selecting an adsorber bed with small adsorbate penetration depth and ability to work with a variety of working pairs is preferred. To this end, finned tube adsorber bed design seems to be a better candidate among the existing designs.

As shown in Table 1, the studies conducted with finned tube adsorber beds show a variety of SCPs, adsorber bed to adsorbent mass ratios and COPs. To make the analysis easier, the effects of different finned tube adsorber bed designs are illustrated on the performance of waste-heat driven ACS in Fig. 5. The data shown in Fig. 5 are sorted based on the ascending SCP.

The gray region demarcated in Fig. 5 is selected based on the desired values for the ACS performance mentioned in Section 4.3. The finned tube adsorber beds used by Freni et al. [110], Verde et al. [112], and Sapienza et al. [113] and Aristov et al. [114] reported to achieve SCP of 137–318 W/kg dry adsorbent, adsorber bed to adsorbent mass ratio of 1.8–4.5, and COP of 0.15–0.29. The common features of these adsorber beds, depicted in Fig. 6, are a large number of fins to increase heat transfer surface area and small fin spacing to decrease adsorbent thickness. However, none of these heat exchangers are specifically designed for an ACS adsorber bed. For example, the heat exchanger used by Sapienza et al. and Aristov et al. is an off-the-shelf air-cooled heat exchanger manufactured by Valeo Thermique [113,114].

Although adsorber beds shown in Fig. 6 result in better performance, the cooling capacity of ACS designed by Freni et al. [110], Verde et al. [112], and Sapienza et al. [113] and Aristov et al. [114] are 480 W, 1.9 kW and 155 W with adsorbent mass of 1.75, 3 and 0.35 kg/bed, respectively. The calculation in Section 4.3 shows that to build a 1-TR (3.517 kW) ACS, 5 kg adsorbent per bed is required. As such, using off-the-shelf finned tube heat exchangers increase the volume and mass of the adsorber bed. As a consequence, a new finned tube adsorber bed, which is specifically sized and optimized for waste-heat driven ACS, should be designed and to improve its performance, the following suggestions should be considered:

- Optimization of fin spacing vs. the weight and volume of the finned tube adsorber bed.
- Calculation of proper fin height in the finned tube adsorber bed to have an effective heat transfer and, also, appropriate adsorbent thickness.
- Enhancing thermal conductivity of adsorbent materials, e.g. by adding metallic wire mesh and wire wool between adsorbent particles [124].

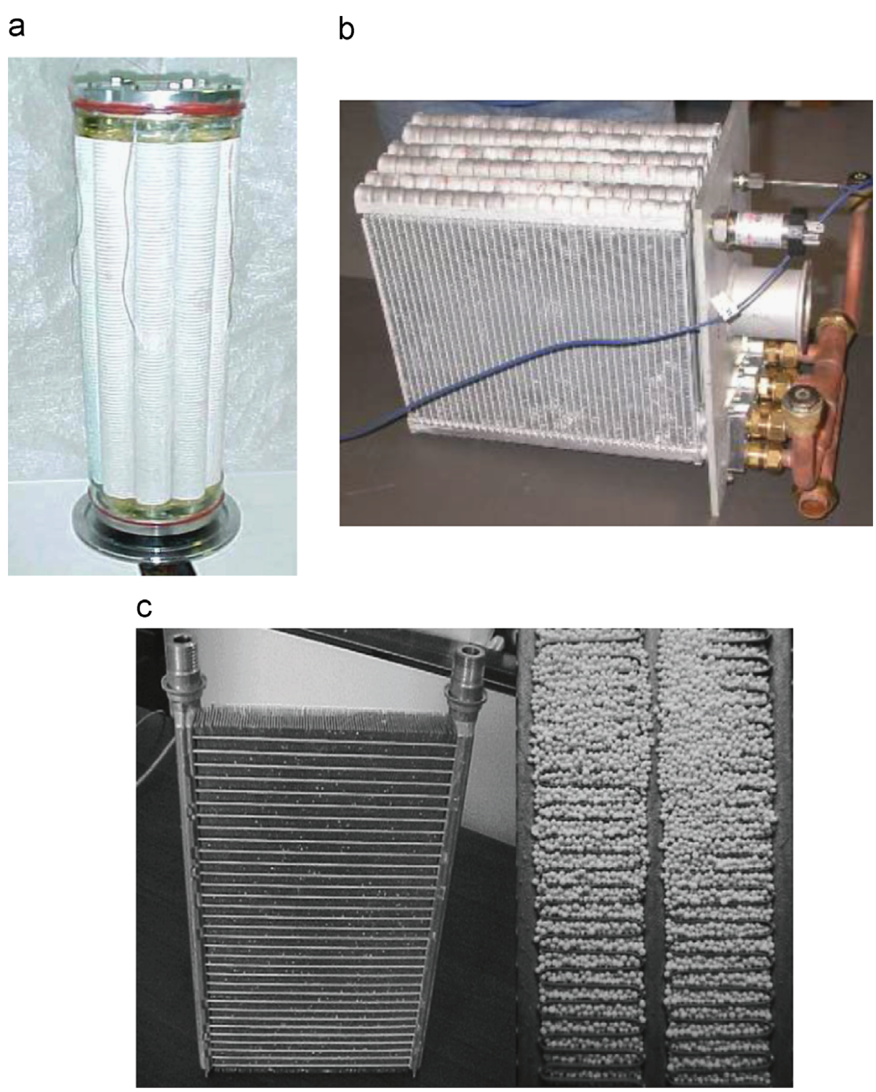


Fig. 6. The finned tube adsorber beds used in waste-heat driven ACS reported with high SCP. (a) Freni et al. [110], (b) Verde et al. [112], (c) Sapienza et al. [113] and Aristov et al. [114].

7. Conclusion

In this study, the effects of different available adsorber bed types were studied on the performance of waste-heat driven ACS for vehicle A/C–R applications. To assess the performance of ACS, the SCP, adsorber bed to adsorbent mass ratio and COP were used and their importance were explained. The SCP of 350 W/kg dry adsorbent, adsorber bed to adsorbent mass ratio of less than one were estimated as desired values for a 1-TR ACS. To this end, previous studies available in the literature were categorized based on their working pair, cooling capacity, COP, SCP, cycle time, and adsorber bed to adsorbent mass ratio. Based on the tabulated data, the adsorber beds were classified into nine types: (1) Spiral plate, (2) Shell and tube, (3) Hairpin, (4) Annulus tube, (5) Plate fin, (6) Finned tube, (7) Plate-tube, (8) Simple tube, and (9) Plate. Based on the estimated desired values for the 1-TR ACS, finned tube adsorber bed design was observed to have a better performance among the existing adsorber beds. Finally, prominent finned tube adsorber bed designs, based on the reported data, were selected for vehicle A/C–R applications and practical solutions, namely, optimization of fin spacing and fin height in finned tube adsorber beds, and increasing thermal conductivity of adsorbent materials, were proposed to increase heat and mass transfer rates inside the adsorber beds.

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